

Investigation of cutting-induced damage in CMC bend bars

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Abstract. Ceramic matrix composites (“CMC”) with a strong fibre-matrix interface can be made damage-tolerant by introducing a highly porous matrix. Such composites typically have only a low interlaminar shear strength, which can potentially promote damage when preparing specimens or components by cutting. In order to investigate the damage induced by different cutting methods, waterjet cutting with and without abrasives, laser-cutting, wire eroding and cutoff grinding were used to cut plates of two different CMCs with a matrix porosity up to 35 vol.-%. For each combination of cutting method and composite, the flexural and interlaminar shear strength of the resulting specimens was determined. Additionally, the integrity of the regions near the cut surfaces was investigated by high-resolution x-ray computer tomography. It could be shown that the geometrical quality of the cut is strongly affected by the cutting method employed. Laser cut and waterjet cut specimens showed damage and delaminations near the cut surface leading to a reduced interlaminar shear strength of short bend bars in extreme cases.

1. Introduction

In recent years non-conventional cutting methods such as wire eroding, waterjet and laser cutting have become popular for cutting composites due to advantages such as flexibility to cut in any direction, low cutting forces and decent cutting speeds [1, 2]. The absence of tool wear makes these methods also attractive for cutting ceramic composites. All cutting methods will apply local mechanical and/or thermal loads to the material near the cut surface which can cause damage in the affected zone. The question arises which cutting methods can be safely used to cut testing specimens for mechanical tests of CMC with only moderate interlaminar shear strength. The proposed contribution will study the effects of five different cutting methods (waterjet cutting with and without abrasives, laser-cutting, wire eroding and cut-off grinding) on the flexural and interlaminar shear strength of cut bend bars of two different CMCs with a relatively high matrix porosity.

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2. Experimental

2.1 Investigated composites

Two composites, namely FU 2998/1 (Schunk Kohlenstofftechnik, Heuchelheim, Germany) and SiCARBON™ (Airbus Group Innovations, Munich, Germany) were studied in the scope of the present work. FU 2998/1 is based on woven 0/90° fabrics of 3M Nextel™ 610 alumina fibres. For composite fabrication 8 fabric layers were laminated, and the matrix was formed by PIP (polymer infiltration and pyrolysis) using a polysiloxane polymer filled with SiC particles. The resulting composite had a fibre content of approx. 50 vol.-% and a total porosity of 16 vol.-%. SiCARBON™ is a C_f/SiC composite produced by the PIP process (polymer-infiltration-pyrolysis). The investigated composite consisted of a lay-up with sixteen 0/90° layers and was formed by filament winding of continuous carbon fibres (T800-6K, TORAY, Japan) and a pre-ceramic slurry. The studied composite was then re-infiltrated with a liquid pre-ceramic polymer and pyrolyzed three times resulting in a fibre content of approx. 50 vol.-% and a total porosity of 17 vol.-%.

2.2 Preparation of specimens

The studied composites were provided in the form of rectangular plates of 2.3 to 3 mm thickness by the manufacturers. The structural integrity of the composite plates was controlled by X-ray and ultrasonic inspection. Bend bars (with fiber orientation 0°/90°) were cut from the composite plates using different cutting methods:

- 1) Waterjet cutting without addition of abrasives using a water pressure of 370 MPa and a feed rate of 0.5 m/min resulting in a kerf width of 0.12 mm.
- 2) Abrasive waterjet cutting with a feed rate of 1m/min and a water pressure of 370 MPa. Garnet sand (80 mesh) was used as abrasive, and the resulting kerf width was 0.9 mm.
- 3) Cutoff grinding using a 1.5 mm thick synthetic resin bond diamond grinding wheel, a water-based cooling lubricant and a moderate material removal rate.
- 4) Wire eroding (wirecut EDM) using a brass cutting wire and a cutting speed of 1 mm/min.
- 5) Laser cutting using a continuous wave CO₂ laser with 5 kW power. The focus width was 200 μm and the cutting speed was 1.2 m/min.

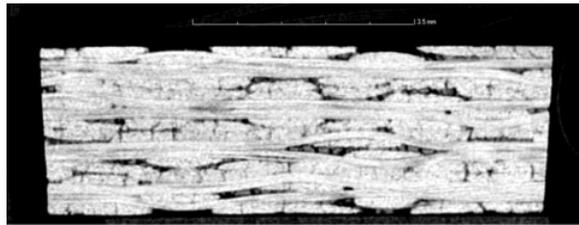
After cutting, the density and open porosity of coupons from each plate was measured using the buoyancy method according to the European standard EN 1389 [3]. The immersion liquid was a water/octanol mix (mixing ratio 1000:1). All cut bend bars were inspected by high resolution X-ray computer tomography (μ -CT) on an industrial CT machine (HR-150-03). The X-ray source was powered at 100 kV, with a current of 150 μ A, producing a polychromatic X-ray spectrum suited for analyzing both types of specimens. The reconstruction was based on 1600 individual X-ray radiography images with a resolution of 12 microns. Reconstruction of the cross-sections was performed using a reconstruction algorithm developed at the Fraunhofer Institute EZRT in Fürth, Germany. Structural analysis and three-dimensional visualizations were carried out using the software VG-Studio Max, version 2.2.

2.3 Mechanical testing

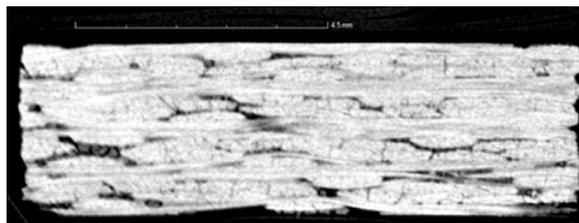
The interlaminar shear strength was tested by a short span bend test according to EN 658 part 5 [4] with a ratio of span width L to specimen thickness d of 5 resulting in a span width of 11.5 to 15 mm. The flexural strength of the cut bars was tested in three- point bending according to EN 658 part 3 [5]. For the latter test two different specimen widths were used – namely 9 mm and 19 mm (with up to 1 mm variation due to different kerf widths produced by the different cutting methods). Experimental details and specimen dimensions can be found in Table 1.

Table 1. Test details.

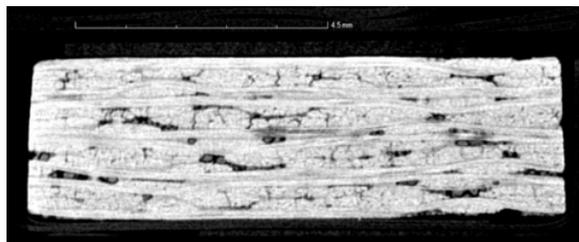
Test	Specimen cross section	No of tested specimens	Span width
Interlaminar shear strength	$8-9.5 \times 2.3-3 \text{ mm}^2$	10-12	11.5-15 mm
Flexural strength	$8-9.5 \times 2.3-3 \text{ mm}^2$	10-12	100 mm
Flexural strength (extra wide specimens)	$18-19.5 \times 2.3-3 \text{ mm}^2$	6	100 mm



a) cutoff grinding (CG)



b) waterjet cutting (WJ)



c) abrasive waterjet cutting (AWJ)



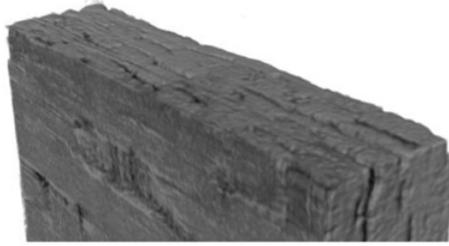
d) laser cutting (LC)

Figure 1. μ -CT Cross section of Schunk FU2998/1 specimens cut with different methods. The cut surfaces are on the left and right of the image.

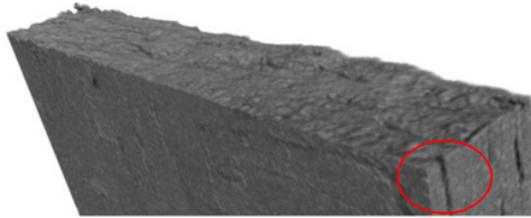
3. Results

3.1 Results for Schunk FU2998/1

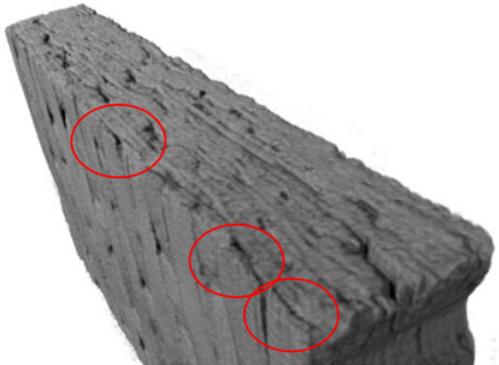
μ -CT images of cross sections of a cut bend bar are shown in Fig. 1. 3D views of the cut surfaces are shown in Fig. 2. It is obvious that the used cutting methods produce cuts of different quality. The



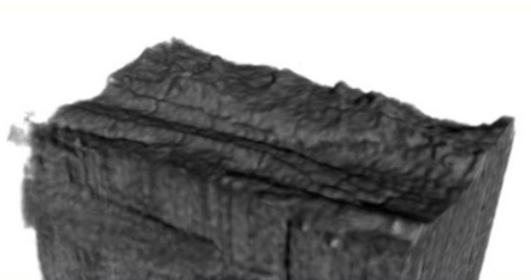
a) cutoff grinding (CG)



b) waterjet cutting (WJ)



c) abrasive waterjet cutting (AWJ)



d) laser cutting (LC)

Figure 2. 3D-view of the surface morphology of Schunk FU2998/1 specimens cut with different methods. The cut surface is facing up, the exit surface of the waterjet beam is on the left.

Table 2. Flank angle and width variations (intraspecimen) determined by μ CT-data for Schunk FU2998/1.

Method	Flank Angle	Interspecimen flank angle variation	Intraspecimen true width variation
Cutoff grinding	$2.9^\circ \pm 0.1^\circ$	moderate	0.29 mm
Waterjet cutting	$3.2^\circ \pm 0.3^\circ$	moderate	0.21 mm
Abrasive waterjet cutting	$1.8^\circ \pm 0.4^\circ$	moderate	0.28 mm
Laser cutting	$4.1^\circ \pm 4.0^\circ$	high	0.55 mm

side surfaces of cutoff-ground specimens are smooth (Figs. 1a and 2a), but the cut was sometimes not perfectly perpendicular to the specimen top surface (an example is shown Fig. 1a, the observed flank angle varied somewhat from specimen to specimen). Waterjet cut specimens had a more irregular surface (Figs. 1b and 2b). In some places, slightly delaminated top layers could be observed near the exit surface (encircled areas in Fig. 2b). Waterjet cutting with particle addition resulted in a smoother cut surface (Figs. 1c, 2c) with slightly rounded edges near the exit surface of the waterjet (edges at the top of Fig. 1c). Again, slightly delaminated top layers could be observed near the exit surface (encircled areas in Fig. 2c). Laser-cutting resulted in evident surface defects with molten regions on the cut surface (bright areas in Fig. 1d). Superficial cracks were also visible on the cut surfaces. The heat affected zone was very brittle and material could be easily removed by slight mechanical contact leading to a very irregular surface (Fig. 2d).

Table 2 shows the measured flank angle and width variation of selected Schunk FU2998/1 coupons (only one specimen of each type was analysed in detail). For all cutting methods flank angles were significantly different from 0° (i.e. the cut surfaces were not exactly perpendicular to the plate surface). The variation of the observed flank angle within one specimen was very low (0.4° or lower) for all cutting methods except laser cutting. The flank angle variation from specimen to specimen was larger and could reach 2° for all methods. The combined effect of non-zero flank angles and surface irregularities leads to a non-constant distance between points on opposite cut surfaces (hereafter called “true width”). The true width varied approx. 0.2–0.3 mm within one coupon except for laser cutting where the true width variations could reach 0.6 mm.

The flexural strength of Schunk FU2998/1 specimens cut by different methods is shown in Fig. 3. Within experimental uncertainty, no significant difference in the determined three-point bending strength could be determined for the eight specimen groups. It is interesting to note that the determined average bending strength of the wider specimens was slightly higher for all cutting methods. Although the differences were not statistically significant, this may be a hint that the non-ideal surface topography can lead to a lower evaluated strength. Compared to the other groups, the laser cut specimens showed a large strength scatter (standard deviation) resulting in the largest uncertainty in the determined average value.

The interlaminar shear strength (ILSS) of Schunk FU2998/1 specimens cut with different methods is shown in Fig. 4. WJ and AWJ specimens were taken from one composite plate, CG and LC specimens from another plate with a slightly thinner matrix between the fibre layers. Nevertheless, within experimental error, the ILSS of cutoff-ground and the waterjet cut specimen groups were almost identical, and the laser-cut specimens had significantly lower interlaminar shear strength.

3.2 Results for airbus group SiCARBON™

μ -CT images of cross sections of cut SiCARBON™ bend bars are shown in Figs. 5 and 6. Again, the employed cutting methods produce cuts of different quality. The side surfaces of cutoff-ground specimens (Figs. 5a, 6a) are smooth, but in some cases the cut was not perfectly perpendicular to the specimen top surface. Waterjet cut specimens had a more uneven surface (Figs. 5b, 6b) with slightly

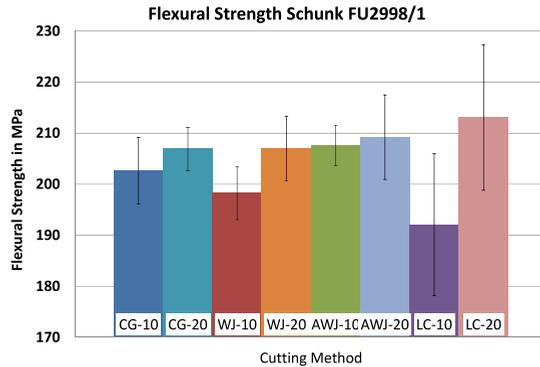


Figure 3. Flexural strength (3-point-bending) of Schunk FU2998/1 specimens cut with different methods: cutoff grinding (CG), waterjet cutting (WJ, with particles AWJ) and laser cutting (LC). The number after the cutting method indicates the width of the specimens (10 – narrow, 20 wide specimens). The error bars indicate 90% confidence intervals.

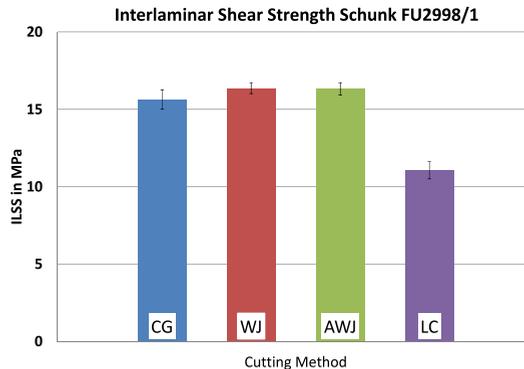
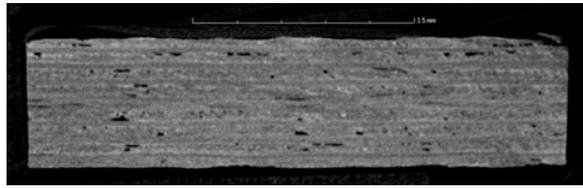


Figure 4. Interlaminar shear strength of Schunk FU2998/1 specimens cut with different methods as determined in short bending: cutoff grinding (CG), waterjet cutting (WJ, with particles AWJ) and laser cutting (LC). The bars on the columns indicate 90% confidence intervals.

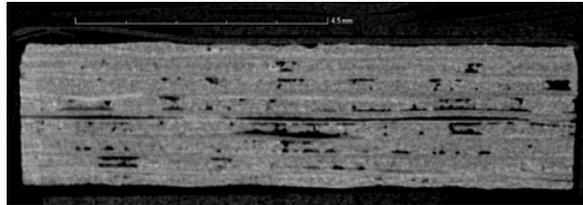
rounded edges near the exit surface of the waterjet (Fig. 5b). In some locations (encircled in Fig. 6b) delamination could be detected near the exit surface. The observations for waterjet cutting with particle addition (Figs. 5c, 6c) are nearly identical to those without particle addition. Wire eroding resulted in almost perfectly perpendicular side surfaces (Fig. 5d). Grooves parallel to the fibre layers could be observed (Fig. 6d). Close inspection by high-resolution μ -CT showed that the grooves were caused by missing fibres – it is believed that these superficial fibres were burnt away during eroding by the discharge.

Table 3 shows the measured flank angle and width variation of selected SiCARBON™ coupons. Only one specimen of each type was evaluated. For waterjet cutting (with or without particle addition) flank angles were significantly different from 0° . The variation of the observed flank angle within one specimen was below 0.4° for all cutting methods. The flank angle variation from specimen to specimen is larger and can exceed 2° for all cutting methods except wire eroding. The true width varied by 0.06–0.25 mm within one coupon with the smallest width variations found for cutoff-grinding and wire erosion.

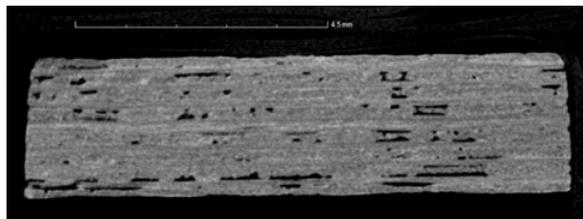
Results for the flexural strength of SiCARBON™ specimens cut by different methods are shown in Fig. 7. The average three-point bending strength was about 460 MPa. With the exception of WJ-10



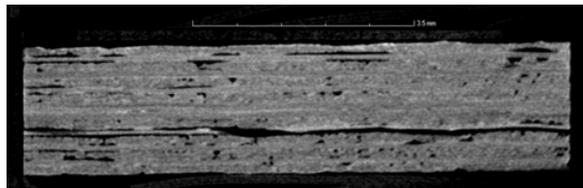
a) cutoff grinding (CG)



b) waterjet cutting (WJ)



c) abrasive waterjet cutting (AWJ)



d) wire eroding (WE)

Figure 5. μ -CT Cross section of SiCARBON™ specimens cut with different methods. The cut surfaces are on the left and right of the image.

(narrow water jet cut specimens), the 90% confidence interval of all specimen groups overlapped. The waterjet cut specimens were also the only group showing a dependence of the flexural strength on the specimen width. The strength scatter was higher than for Schunk FU2998/1 and did not show significant differences between the specimen groups.

The ILSS of SiCARBON™ specimens cut with different methods is shown in Fig. 8. The specimens prepared by abrasive waterjet cutting showed somewhat lower interlaminar shear strength (11.1 MPa) when compared to the other groups (12.9–13.6 MPa).

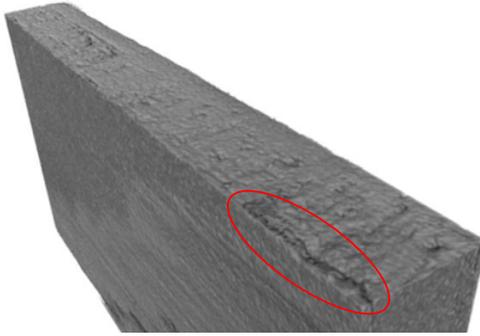
4. Discussion

4.1 Cutting methods and testing standards

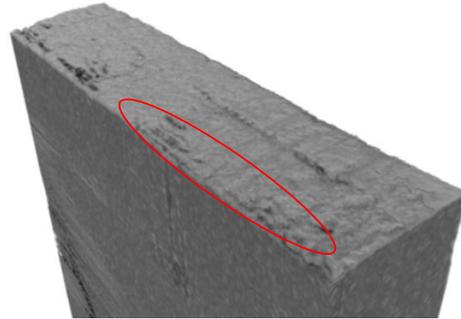
Both, EN 658 part 3 and part 5 state that machining of the specimen has to be carried out in such a way that damage of the material is avoided. These standards state also that the maximum width



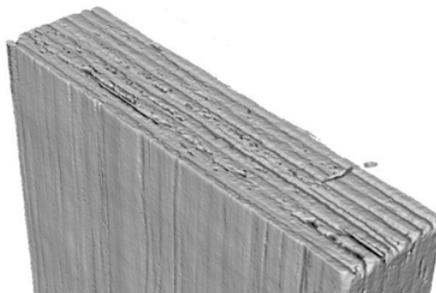
a) cutoff grinding (CG)



b) waterjet cutting (WJ)



c) abrasive waterjet cutting (AWJ)



d) wire erosion (WE)

Figure 6. 3D-view of the surface morphology of SiCARBON™ specimens cut with different methods. The cut surface is facing up, the exit surface of the waterjet beam is on the left.

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Table 3. Flank angle and width variations (intraspecimen) determined by μ CT-data for SiCARBON™.

Method	Flank Angle	Interspecimen flank angle variation	Intraspecimen width variation
cutoff grinding	$1.2^\circ \pm 0.1^\circ$	moderate	0.07 mm
waterjet cutting	$2.4^\circ \pm 0.3^\circ$	moderate	0.17 mm
waterjet cutting with particles	$4.6^\circ \pm 0.4^\circ$	moderate	0.25 mm
wire eroding	$0.6^\circ \pm 0.1^\circ$	very low	0.06 mm

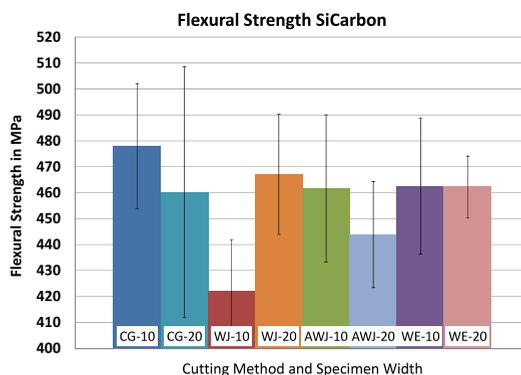


Figure 7. Flexural strength (3-point-bending) of SiCARBON™ specimens cut with different methods: cutoff grinding (CG), waterjet cutting (WJ, with particles AWJ) and wire erosion (WE). The number after the cutting method indicates the width of the specimens (10 – narrow, 20 wide specimens). The error bars indicate 90% confidence intervals.

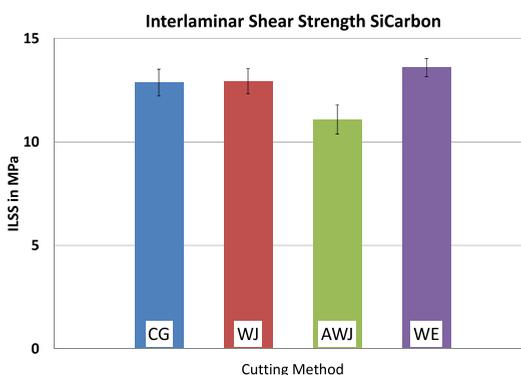


Figure 8. Interlaminar shear strength of SiCARBON™ specimens cut with different methods as determined in short bending: cutoff grinding (CG), waterjet cutting (WJ, with particles AWJ) and laser cutting (WE). The bars on the columns indicate 90% confidence intervals.

variation within one specimen should not exceed ± 0.2 mm (EN 658 part 3) and ± 0.1 mm, respectively (EN 658 part 5). Looking at the specimen surfaces (Figs. 2 and 5) and Tables 2 and 3 it is clear that these requirements are not met by all employed cutting methods. Both, material damage and geometry deviations exceeding the limits are observed. The observations concerning the different cutting methods are summarized in Table 4. No distinction is made between the results of the two studied materials as they showed similar behaviour with respect to cutting quality achieved – the differences in measured flank angles (Tables 2 and 3) are not significant due to the variability from specimen to specimen. The

Table 4. Assessment of different cutting methods with respect to the requirements of EN 658 parts 3 and 5. The assessment is valid only for the prevalent cutting conditions.

Cutting Method	No material damage as required by the standards	Specimen width variation according to standards
Cutoff-grinding	Yes	Not always
Waterjet cutting	No (partially delaminated top layers)	No (width not constant)
Waterjet cutting using abrasives	No (partially delaminated top layers)	No (width not constant)
Laser cutting	No (cut surface with molten regions)	No (irregular surface and varying width)
Wire eroding	Yes, but superficial fibres burnt	Yes

larger width variations in Schunk FU2998/1 compared to SiCARBON™ are mainly due to a larger specimen height (3 mm) of the former which emphasises the effect of non-zero flanking angles.

The mentioned standards propose to measure the specimen width using micrometre gauges with a precision of ± 0.1 mm or better. For the geometrical deviations observed here (trapezoid specimen and uneven cross sections), micrometer screws will typically only measure the maximum specimen width within the contact area (of a typical size of several mm^2). This can lead to a width measurement error exceeding 0.2 mm (i.e. $>2\%$) for thick specimens (>3 mm) and large flank angles ($>4^\circ$). It is therefore important to avoid non-perpendicular specimen surfaces – it is likely that better defined geometrical surfaces can be achieved in waterjet and laser cutting by tilting the beam with respect to the plate or using thinner composite plates. The reason for fluctuating non-zero flank angles in cutoff-grinding is probably the use of a thin (1.5 mm) grinding wheel which can easily bend upon mechanical contact. It is therefore advisable to use a stiffer (thicker) grinding wheel for cutoff-grinding to guaranty perpendicular cut.

4.2 Effect of cutting methods on the determined flexural strength of weak matrix composites

It is well known that surface flaws induced by machining can reduce the strength of ceramics [6] and glass ceramics [7]. In these materials the flaws act as stress concentrators which can induce failure upon mechanical loading. For this reason, the European testing standard for such materials gives precise instructions how the faces specimens from such materials have to be machined and prescribes bevelled edges of bending specimens [8].

When looking at Figs. 3 and 7, it is obvious that the different surface quality did not have a significant effect on the determined flexural strength of the tested ceramic matrix composites due to their inherent damage tolerance. It is particularly instructive to compare the strength for identical cutting methods, but different specimen width. If fibre damage induced by cutting would be relevant for flexural strength, one would expect that wider specimens would be less affected as only fibres near the cut surface would be damaged.

For Schunk FU2998/1 (Fig. 3), there is no significant difference in flexural strength between the specimen groups with approx. 10 mm and 20 mm width for any of the cutting methods. Even for laser cut specimens, the average value of the flexural strength does not differ from specimen groups cut by other methods despite the molten zones observed at the cut surface. However, the strength scatter (standard deviation) is significantly larger for this specimen group. It is believed that the larger scatter in strength is mainly due to difficulties in determining the width of the specimens precisely – the surface is irregular and the measured specimen width also shows a larger scatter compared to the other specimen groups.

For SiCARBON™ (Fig. 7), the only significant difference is observed for the specimen groups WJ-10 and WJ-20 (421 MPa vs. 467 MPa). Inspection of the strength data of individual specimens

showed that the relatively low strength of the specimen group is mainly caused by five specimens which were cut from adjacent locations in the composite plate. It is therefore believed that the lower strength of this group is caused by a local fluctuation in material properties rather than being a result of cutting damage. This is further supported by the fact that the groups AWJ-10 and AWJ-20 had both a flexural strength similar to WJ-20 (namely 462 MPa and 444 MPa) despite showing similar cutting damage. It can be concluded that waterjet cutting can induce local delamination in weak matrix composites, but the small delaminated zones near the specimen edge do not have an effect on flexural strength.

4.3 Effect of cutting methods on the determined interlaminar shear strength of weak matrix composites

In contrast to flexural strength where failure is dominated by the fibres, interlaminar shear strength is limited by the matrix, and failure may be initiated from matrix flaws on the side of the short bending specimen. It was thus expected that short bending tests would be more sensitive to the quality of the cut surface.

Indeed, for Schunk FU2998/1 there is a significant difference in flexural strength between the laser cut and the other specimen groups (Fig. 4). Obviously, interlaminar cracks easily initiate in the rough surface with molten zones and lead to the lower observed interlaminar shear strength of these specimen group. There is also a small difference in interlaminar shear strength between the CG group on the one side and the WJ and AWJ group on the other side. Inspection of the AWJ and WJ specimens showed that they originated from a plate with a slightly thicker matrix layer between the fibre fabrics which explains the small difference in interlaminar shear strength.

For SiCARBON™ the only significant deviation in interlaminar shear strength is observed for the specimen group AWJ. Inspection of the strength data of individual specimens showed that the relatively low strength of the specimen group is mainly caused by three specimens. Two of them were cut from directly adjacent locations and all three originated from the same area and plate as the low strength WJ-10 bending specimens. Due to the fact that delaminated zones were visible already before testing in this material, typically several delamination cracks were observed after the short bend test which made it difficult to safely assess the validity of the test (namely observation of shear failure in the central part of the specimen). It is therefore possible that the lower strength of the AWJ group is caused by pre-existing delaminated regions which may or may not be caused or enlarged by the waterjet cutting process.

Looking at Figs. 2 and 6, it is clear that waterjet cutting (with or without particle addition) can induce small delaminated zones near the specimen edge of weak matrix composites. However, no clear evidence for delamination damage in the central zone of the cut surface was found. In short bending tests, the maximum shear stresses occur in the centre of the specimen and in a valid test, failure must occur in this region. It is therefore likely that, for the two composites studied, the damage caused by waterjet cutting was not detrimental for the determination of interlaminar shear strength.

5. Conclusions

Different cutting methods applied to weak matrix CMCs have produced coupons with varying surface quality:

- Unless special precautions are met, laser and waterjet cutting of ceramic composites can produce specimens with a geometry not meeting the requirements of the EN 658 standard. The deviations may go unnoticed if micrometre screws are used for measurements of the specimen dimensions.
- Laser cutting induced significant thermally induced surface damage and embrittlement which resulted in invalid results for the interlaminar shear strength and excessive scatter of the flexural strength measurements.

- Waterjet cutting can produce a slightly uneven surface and delamination damage near the edges of specimens of weak matrix composites. For the investigated composites, this damage had no significant effect on the determined flexural strength, and the effect on the interlaminar shear strength seemed to be weak or non-existing, but this may differ for composites with even lower ILSS.
- The safest cutting methods for preparing specimens from weak matrix CMCs are cutoff-grinding using (not too thin) grinding wheels and wire eroding. Unfortunately, the latter method only works for electrically conductive composites and both are not very productive.

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